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Case Studies in Engineering Management

Condition Based Maintenance Plus Return on Investment Analysis

Ken Fischer

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Chapter I – Project Overview

Introduction

The United States Army TACOM Life Cycle Management Center (TACOM LCMC) is responsible for the sustainment of all ground vehicle platforms and supporting equipment. Recent military operations in Iraq and Afghanistan have provided evidence that the current approach to vehicle maintenance is not sufficient for meeting the needs of the Warfighter. The maintenance concept known as Condition Based Maintenance Plus (CBM+) is a set of analyses and technologies that are intended to transition the military from the traditional reactionary and time-based preventative maintenance processes to one that delivers maintenance only upon evidence of need. CBM+ is a significant System of Systems (SoS) problem requiring integration of a variety of legacy logistic systems for automation of parts requisitions, as well as onboard computing and sensor systems required to collect and analyze vehicle performance, usage, and maintenance data. Operations & Support (O&S) costs have been estimated to account for anywhere from 60 – 80% of the total cost of ownership for military platforms. The goal of CBM+ is to reduce the life cycle costs and increase the operational availability for these systems. A methodology for assessing the potential return on investment (ROI) must be developed to ensure that these anticipated benefits are likely to be realized prior to investment in CBM+ technology enablers.

Traditional ROI analyses have used deterministic supply, maintenance, and logistics models that are not necessarily integrated with one another. These types of models, while mathematically convenient, make many assumptions with regard to the state of the fleet being analyzed. The results are typically averages for the period of time under analysis, but do not show the time-dependent aspects and dynamics of these integrated processes. A better and more integrated method is needed.

A time-dependent, stochastic, discrete event modeling approach enables an analysis that considers variability in time to diagnose, time to repair, supply chain delays, material reliability, and other dynamics within this SoS process. Consideration of these system interactions is critical for accurately assessing the likely ROI and will allow for analysis of a variety of potential implementation strategies for a given platform. Additionally, these same models can be used to answer many other life cycle management questions including how many spares to order, where they should be positioned, and what components should be targeted for engineering changes to improve reliability.

Problem Definition

The US Army Ground Vehicle community must develop an effective approach to CBM + ROI analysis. The high cost of sustainment, coupled with the recent announcements about significant cuts to DoD budgets, only reinforces the need to save money and improve efficiencies wherever possible. CBM+ has the potential to provide these benefits if implemented properly, but the current deterministic models have proven insufficient for analyzing the complex interactions between the platform and the logistic systems that sustain them. The assumptions underlying the deterministic analyses are so broad and unsubstantiated that the analysis results have little value and are easily called into question. The objective of this case study is to develop a life cycle logistic model that incorporates system interactions and allows for analysis under uncertain conditions. This will enable a more robust ROI analysis and improve the confidence in the analysis results.

Project Assumptions and Limitations

This project utilized the life cycle logistic model to assess the potential ROI for CBM+ implementation. To accomplish this task the following assumptions and limitations were made to appropriately scope the problem.

1. This study focused exclusively on the Heavy Expanded Mobility Tactical Truck (HEMTT) platform. This platform has been identified as a CBM+ system of interest by the Army Materiel Command (AMC).
2. This study leveraged the Reliability Centered Maintenance (RCM) analysis that has already been done on this platform. The intent of RCM is to determine which platform components should be considered for a CBM+ approach to maintenance. Discussion of the RCM analysis will be covered in Chapter II - Literature Review section of this paper.
3. The level of process modeling was driven by the availability of data. The intent was to model the supply chain and maintenance processes including shipping and storage of spares.

Background

Condition based maintenance implementation is being driven by several high level Department of Defense and US Army regulations, instructions, and policy memorandums. Some examples are:

- ***Army Regulation 750-1, 20 Sep 2007, p. 175-*** **CBM+ is a set of maintenance processes and capabilities derived primarily from real-time assessment of weapon system condition obtained from embedded sensors and/or external test and measurements using portable equipment.**

- ***DoDI 4151-22, 2 December 2007, p. 1-*** **CBM+ is the application and integration of appropriate processes, technologies, and knowledge based capabilities to improve the reliability and maintenance effectiveness of DoD systems and components. At its core, CBM+ is maintenance performed on evidence of need provided by reliability centered maintenance (RCM) analysis and other enabling processes and techniques.**

- **The Assistant Secretary of the Army for Acquisition, Logistics and Technology, policy memorandum, "Condition Based Maintenance Plus (CBM+) dated 20 March 2008, requires program managers to conduct a cost-benefit analysis to incorporate CBM+ concepts and technologies in the design and development of new equipment, major weapon systems, and planned upgrades.**

These guidance documents define what CBM+ is and the technology enablers that are required to support its implementation. The level of CBM+ implementation on a given platform is determined through the performance of RCM and Cost-Benefit analyses. RCM helps to define the critical components and failure modes for a given system, and then determines the proper mix of maintenance strategies including opportunities for condition based maintenance approaches. The cost benefit analysis determines if the investment in CBM+ enabling technologies is justified in terms of cost reductions or other tangible benefits to the Warfighter. To this point a financial ROI has been the driving metric required to justify CBM+ implementation.

The Tank Automotive Research Development & Engineering Center (TARDEC) is the engineering support organization for the TACOM LCMC. TARDEC has been supporting many of the CBM+ initiatives across the TACOM LCMC community and has recently agreed to develop an organic capability to perform logistics modeling & simulation analysis. This project directly supports that commitment, and the knowledge gained during the execution of this project will be a first step toward development of this organic capability. The results of this study will also benefit the Program Manager for Heavy Tactical Vehicles (PM-HTV) in developing the ROI analysis for implementation of CBM+ capabilities on this critical platform. The methodology demonstrated in this case study provides a framework for future ROI analyses once real world data is collected and made available.

In addition to these local benefits, AMC has recently requested that an actionable plan be developed for implementation of a CBM+ Pilot Project on a tactical vehicle platform. The planning committee has identified the HEMTT as a potential platform for this pilot project. The methodology demonstrated in this case study can be used to evaluate a variety of candidate platforms and the ROI analysis approach that was used in this case study will directly benefit from the on-platform data collection, which will provide the real world input data that was not available for this case study.

Chapter II – Literature Review

4D / RCM Analysis

The Delayed Desert Damage and Degradation (4D) project was an analysis activity intended to identify cost and maintenance drivers that were attributable to operations in Southwest Asia (Iraq, Afghanistan). This analysis method was tailored slightly in order to perform an RCM analysis to look for the best candidates for CBM+ implementation. One of the most significant lessons learned from this effort was the challenge that the US Army faces with regard to data completeness, accuracy and integrity. There were significantly more part requisitions than maintenance actions logged (4 to 6 times in some cases) without any way to clearly track the cause. There were also many cases of invalid data entries such as empty fields, vehicle serial number "12345", or fault symptom listed as "Broken" or "INOP". As a result of these challenges all of the results had to be supported by maintainer interviews in the field.

Demand data was pulled from the Integrated Logistics Analysis Program (ILAP) maintenance system, the Operation and Support Maintenance Information System (OSMIS) supply system, and the Army Materiel System Analysis Agency's (AMSAA) Sample Data Collection (SDC) initiative. Analysts reviewed these data sources for consistency in results in order to add confidence to their findings. High level Failure Mode and Effects Analysis reports were generated for each of the target components, and the critical failures modes identified were validated against results from field interviews. This process resulted in recommendations for CBM application based on identified need (cost & maintenance drivers) and on viability of condition based maintenance opportunities (critical failure modes that could be sensed).

One of the platforms analyzed under this effort was the HEMTT. The results of the HEMTT analysis showed that engine, transmission, tires, and batteries were at the top of the list for maintenance and cost drivers. Tires were not seen as good CBM candidates due to the lack of sensors available for detecting the critical failure modes. The alternator and starter were determined to be good CBM candidates due to their criticality to system operation and ability to monitor for their critical failure modes. These five components will be analyzed for determining the potential cost/benefit for CBM implementation under this case study project.

TWV CBM ROI Analysis

The Program Manager for Tactical Vehicles (PM-TV) project office was tasked to conduct a ROI analysis for implementing CBM across four different tactical wheeled vehicle (TWV) platforms including the HEMTT. This report considered input from the 4D / RCM Analysis as well as studies conducted by two different industry contractors. This report highlighted many of the data challenges already discussed, and also acknowledged that all of the analyses performed failed to account for all of the sources of potential savings. For instance, this analysis only considered savings that resulted from reduction of failures based on 2007 costs.

Table #1 - #3 below are excerpts from the TWV ROI Report showing the purchase costs for four critical components, a range of costs for the CBM enabling technologies based on 2006 fleet densities, and resulting ROI Period based on percentage of failures avoided. Based on these simplifying assumptions the report author stated that CBM was unlikely to result in a ROI period of less than 10 years.

Table #1 - Part Costs for Candidate Parts for Applying CBM

	Eng	**Trans**	**Batt**	**Altern**	**2007 Costs**
HEMTT	20.9M	3.3M	3.8M		28.0M
FMTV	14.4M	7.4M	9.4M	1.6M	32.8M
HMMWV	32.8M	1.4M	8.1M	8.5M	50.8M
M915 LH	2.2M	1.4M	1.1M		4.7M
					$116.3M

Table #2 - Range of Vehicle CBM Enabling Costs per 2006 Fleet

	$1000	**$2600**	**$5000**	**$7500**
HEMTT@11.5K	11.5M	29.9M	57.5M	86.3M
FMTV@26K	26.0M	67.6M	130.0M	195.0M
HMMWV@119K	119.0M	309.4M	595.0M	892.5M
M915LH@6K	6.0M	15.6M	30.0M	45.0M
Totals-162,500	***162.5M***	***422.5M***	***812.5M***	***1,212.8M***

Table #3 - ROI Period = CBM Enabling Costs / Savings per Year

	$162.5M	**422.5M**	**812.5M**	**1,212.8M**
5% ($ 2.3M/yr)	70.7yrs	183.7yrs	353.3yrs	527.3yrs
10% ($11.6M/yr)	14.0yrs	36.4yrs	70.0yrs	104.6yrs
20% ($23.3M/yr)	7.0yrs	18.1yrs	34.9yrs	52.1yrs
25% ($29.1M/yr)	5.6yrs	14.5yrs	27.9yrs	41.7yrs
50% ($58.2M/yr)	2.8yrs	7.3yrs	14.0yrs	20.8yrs

Using part cost alone ignores savings that can be achieved from reduction in inspection times, reduced logistic down times, and ability to

change the level of repair for diagnosable failure modes. An additional problem with this analysis is the assertion that failures will be reduced. CBM+ does not change the inherent material reliability of the system. Mission Reliability is improved by performing maintenance early, which prevents most failures from occurring during a mission, but the repair action still occurs. CBM+ allows for a proactive maintenance planning strategy that can optimize the use of limited maintenance resources. These additional sources of savings need to be considered in order to accurately estimate the ROI potential for implementing CBM.

CLOE Cost Benefit Analysis

The US Army's Common Logistic Operating Environment (CLOE) is an initiative intended to develop a viable logistic enterprise architecture including the off-platform enablers for CBM+. As part of this initiative a Cost Benefit Analysis (CBA) was completed in order to estimate the potential benefits for implementation of this architecture. This CBA was an improvement over the TWV CBM ROI Analysis in that it attempted to capture the benefits of efficiency improvements in the logistic systems as well as potential cost savings from mission failure avoidance. Some of these additional savings opportunities included reduction in maintenance costs due to reduced mean time to repair (MTTR), and reduced mean logistics down time (MLDT) due to improved forecasting and advanced reporting of impending failures. Additionally, this analysis captured the costs saved through optimizing the delivery of consumables (i.e. fuel & water) to units operating in the field, which is enabled by the real-time consumable reporting capability. This less obvious benefit of CBM+ addresses a significant logistics problem for theatre operations. The results of this analysis showed a ~$10M cost savings across a Stryker Brigade Combat Team (SBCT) of 1045 vehicles in the first 10 years of operation. Table #4 below is an excerpt from the CLOE CBA report.

Table #4 - Estimate of Monetary Costs and Benefits from CLOE Enablers

	FY07 Present Value ($K)
Benefits	
Cost Savings	22,348
Avoided Costs	4,035
Total Benefits	26,383
Costs	
Develop Enablers	2,900
Install Enablers	11,950
Additional Operating Costs	870
Total Costs	15,720
Net Present Value	**10,663**

The cost per vehicle for enablers under this analysis is double the maximum cost considered for the TWV CBM ROI Analysis (~$15K vs $7.5K). This is because the CLOE analysis included all of the enablers for off platform data collection and transfer, which were not considered in the TWV analysis. Even with the higher per platform costs this analysis shows a ROI Period of less than 10 years so it is clear that including these logistic benefits makes a big difference in total cost savings. While this analysis represents a step in the right direction, it still fails to capture the uncertainty that exists in the data and the time dependent nature of the system interactions. The assumptions that were made are stated in the report, but the results are never tested for sensitivity to these assumptions. As a result of these limitations it is difficult to have enough confidence in the analysis results to make the recommendation to invest in these technology enablers.

USMC Autonomic Logistics

The Marine Corp Systems Command Program Management Office for Autonomic Logistics (USMC PM-AL) has invested in a logistic forecasting tool that is based on discrete event stochastic simulation. This analysis tool has modeled many of the interactions between a vehicle platform and the logistic systems that support it. It allows for a detailed vehicle data model with up to five levels of indenture. This tool allows the user to define failure rates, repair, and shipping times as probability distributions (weibull, log normal, etc) or as constants. The USMC PM-AL office has successfully used this tool to evaluate a variety of life-cycle cost savings proposals.

The ability of this tool to incorporate uncertainty in time distributions as well as simulate the system interactions over a user defined time frame provides a much more robust analysis framework. Additionally, the use of

discrete event simulation is a time efficient method for running designed experiments that allow for sensitivity analysis of output metrics to a variety of input parameter values. As a result of the benefits discussed above, the Clockwork Solutions Inc. Total Life Cycle Management Assessment Tool (TLCM-AT) will be used to support the analysis for this case study project.

Chapter III – Data Collection

Data Collection Overview

Data collection for the HEMTT proved to be extremely challenging. The summary data obtained from the reports listed in Chapter II provides some insight into the big picture, but lacks the detail for independent analysis. Several attempts to obtain data from the PM-HTV program office failed and due to the time constraints of this case study project a different approach was needed.

As a result of the challenges listed above, data for this project was acquired from a variety of data sources. All of this data was in the form of summary values, which is sufficient for estimating model input parameters. Cost estimates for enabling technologies ($15K est.) were taken from the CLOE CBA since it appears to be a worst case scenario from the analysis performed to date. Operational Tempo (OPTEMPO) estimates were derived from data collected by the Army Materiel Systems Analysis Agency (AMSAA) and the CLOE CBA. Vehicle data and logistic model parameters (failure rates, repair and shipping times, part costs, etc) were taken from estimates obtained by Clockwork Solutions Inc. in support of their USMC initiatives. The labor costs were made up but seem reasonable for the level of repair and skills required, and they are easily updated in the cost calculations if needed. The location and density of the HEMTT fleet were based on the TACOM LCMC TWV CBM+ Pilot Project Plan. This will allow the model to be refined as real data is collected on these platforms. The maintenance structure was defined with each base having its own intermediate level of repair, and all bases sharing a common depot level repair facility. This structure will allow for an evaluation of change in level of repair based on CBM+ implementation. Table #5 below summarizes the sources of data used in this study.

Table #5 – Data Sources

Data Type	Source
CBM Implementation Cost	CLOE CBA
Vehicle Data Model	USMC estimates
Shipping Data Model	USMC estimates
LRU Cost Model	Replace - USMC est. / Other - Hypothetical
Fleet Density	TACOM TWV CBM+ Pilot Project Plan
OPTEMPO	CLOE CBA / AMSAA Report
Maintenance Structure	Hypothetical

Data Definition

The TLCM-AT software operates on a series of MS Access database tables. It was necessary to solicit assistance from the Clockwork Solution Inc. staff (Mr. Tom Virant) to develop the baseline data model including locations, fleet densities, and the vehicle work breakdown structure (LRUs). The TLCM-AT software requires a valid model in order to function. Once the baseline model was established all changes to model parameters were made from within the TLCM-AT Scenario Editors. All of the database files are contained on disk in the appendix. Tables #6 - #10 provide a description of the Scenario Editors that were used to update the model parameters in this project.

Table #6 - Unscheduled Removal Rates Scenario Editor

Parameter Name	Description
MTTF	Failure Rate Mean Time To Failure (mean miles in this case). Is converted into Weibull Alpha value in the background.
Shape	Failure Rate Beta value for Weibull. Value = 1 (Exp Dist) used for this case study due to lack of knowledge about the real reliability model shape and starting age of the systems. All platforms assumed to be in normal operation and not subject to infant mortality or wearout problems.

Note: Data is entered for each LRU in the entire model, which allows for the user to define different failure rates dependent on location as well as LRU type. Failure rate was held constant across all locations in this project.

Table #7 - Logistic Consequences Scenario Editor

Parameter Name	Description
No Action	Probability that no action is taken when a part fails. This parameter is not used in this case study (Value = 0)
No Fault Found	Probability of No Fault Found when a part fails. Inspect only.
Discard	Probability that a part is not repairable when it fails. Inspect only.
Repair	Probability that a part is repaired when it fails. Inspect and repair events will occur.

Note: The sum of the above parameters must equal one to be valid. Logistic consequences were held constant across all locations in this project.

Table #8 - Evac Probabilities Scenario Editor

Parameter Name	Description
Prob	Probability that an item cannot be repaired at a given level of repair and must be sent to the next higher level.

Note: Entered for each combination of level of repair (Operational, Intermediate, Depot) and LRU type.

Table #9 - Maintenance Task Times Scenario Editor

Parameter Name	Description
Type	**Build** – # of days required to reassemble into the next higher level assembly. (Not used) **Inspect -** # of days required to inspect / troubleshoot / diagnose the failure of an item. **Repair -** # of days required to repair the item. **Tear -** # of days required to remove the item from the next higher level assembly. Only used at operational level to remove LRU from vehicle.
Distribution	Enter probability distribution to be used or "Constant" if none. All times assumed to be constant since data was unavailable for determining the real time distributions.
Mean	Mean value of the chosen distribution or fixed value if Constant.
Std Dev	Standard deviation of the chosen distribution or 0 if Constant. Value = 0 for this project.

Note: Entered for each combination of level of repair (Operational, Intermediate, Depot) and LRU type.

Table #10 - Shipment Times Scenario Editor

Parameter Name	Description
Distribution	Enter probability distribution to be used or "Constant" if none. All times assumed to be constant since data was unavailable for determining the real time distributions.
Mean	Mean value of the chosen distribution or fixed value if Constant.
Std Dev	Standard deviation of the chosen distribution or 0 if Constant. Value = 0 for this project.

Note: Entered for each combination of levels of repair (Operational to Intermediate, Intermediate to Depot, and back).

Baseline Data Values

Tables #11 - #15 list the specific data values that were used for the baseline model.

Table #11 - Vehicle Data Model Baseline Values

Scenario Editor	Parameter Name	Platform	LRUs				
		HEMTT	Engine	Transmission	Battery	Alternator	Starter
Unscheduled Removal Rate	Rate (# / 1000 miles)	N/A	0.00179	0.00203	0.00814	0.00358	0.00349
	Shape	1	1	1	1	1	1
Logistic Consequences	No Action	0	0	0	0	0	0
	No Fault Found	0	0	0	0	0	0
	Discard	0	0.239	0.2	0.8	0.15	0.2
	Repair	1	0.761	0.8	0.2	0.85	0.8
Evac Probabilities	Prob	0	1	1	0	1	1
Maintenance Task Time Level of Repair = Oper Type = Inspect	Mean (days)	.2	0	0	.1	0	0

Table #11 - Vehicle Data Model Baseline Values (cont)

Scenario Editor	Parameter Name	Platform	LRUs				
		HEMTT	Engine	Transmission	Battery	Alternator	Starter
Maintenance Task Time Level of Repair = Oper Type = Repair	Mean (days)	0	0	0	0.25	0	0
Maintenance Task Time Level of Repair = Oper Type = Tear	Mean (days)	0	1	1	0.5	0.5	0.5
Maintenance Task Time Level of Repair = Inter Type = Inpsect	Mean (days)	0	0.5	0.5	0	0.1	0.1
Maintenance Task Time Level of Repair = Inter Type = Repair	Mean (days)	0	3	3	0	0.1	0.1

Table #11 - Vehicle Data Model Baseline Values (cont)

Scenario Editor	Parameter Name	Platform	LRUs				
		HEMTT	Engine	Transmission	Battery	Alternator	Starter
Maintenance Task Time Level of Repair = Depot Type = Inspect	Mean (days)	0	0.5	0.5	0	0.1	0.1
Maintenance Task Time Level of Repair = Depot Type = Repair	Mean (days)	0	6	6	0	0.1	0.1

Table #12 - Shipping Data Model Values

From Location	**To Location**	**Time (Days)**
Operational	Intermediate	1
Operational	Depot	17
Intermediate	Depot	17
Intermediate	Operational	1
Depot	Intermediate	62
Depot	Operational	62

Table #13 - LRU Cost Model Values

LRU	Level of Repair	Labor ($/hr)	Parts	Replace
Engine	Intermediate	$50	$5650.58	$45204.60
	Depot	$100	$11301.15	
Transmission	Intermediate	$50	$4641.72	$37133.70
	Depot	$100	$9283.43	
Battery	Operational	$30	$37.62	$75.24
Alternator	Intermediate	$50	$280.99	$2247.87
	Depot	$100	$561.97	
Starter	Intermediate	$50	$183.70	$734.79
	Depot	$100	$367.40	

Table #14 - Fleet Density Values

Location	Quantity	Location	Quantity
AFGHANISTAN	10	FORT HOOD	10
CAMP MURRAY	5	FORT RILEY	5
FORT BLISS	120	FORT SILL	30
FORT CARSON	20	KUWAIT	10
FORT DRUM	10	SEATTLE	10

Table #15 - OPTEMPO Estimation

OPTEMPO Estimates in Miles/Month			
Garrison Training	Intensive Training	Deployed	Reset
714	811	1082	357
ARFORGEN Duty Cycle (Months)			
	FY08	FY09	FY10
Garrison Training	8	9	
Intensive Training		3	
Deployed			12
Reset	4		
Calculated OPTEMPO (Miles per Quarter)			
	Not Deployed	Deployed (Afghanistan & Kuwait)	
OPTEMPO	2000	3250	

Note: Army Force Generation (ARFORGEN) includes all of the cycles that units go through as they prepare for their deployment rotation. The OPTEMPO for non-deployed units was calculated as a ratio of time spent in the three non-deployed ARFORGEN cycles.

Chapter IV – Methodology

Basic Model Outline

The TLCM-AT software operates on several interconnected models. The overall structure of the logistic system model is represented in Figure #1 below. This illustrates the interconnectedness of the various system components. Each functional area is a system in itself thus giving rise to the System of Systems concept.

Figure #1 – Logistic System Interaction Diagram

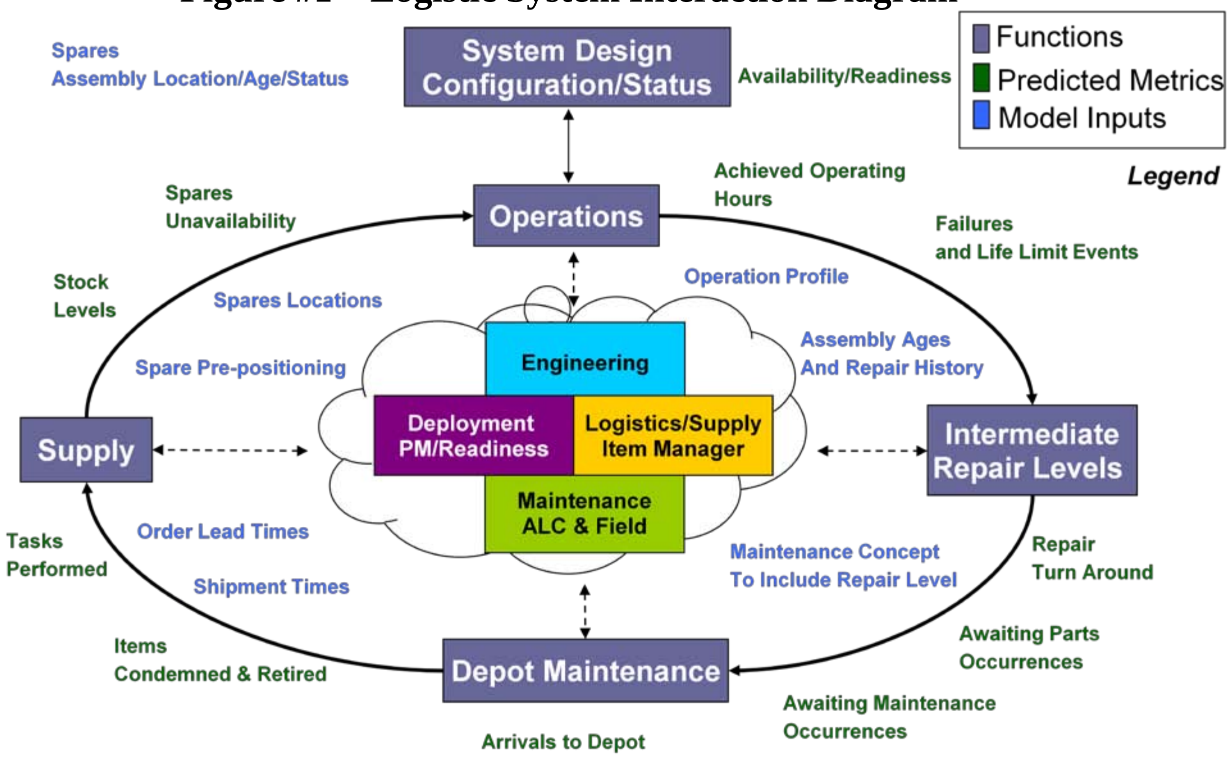
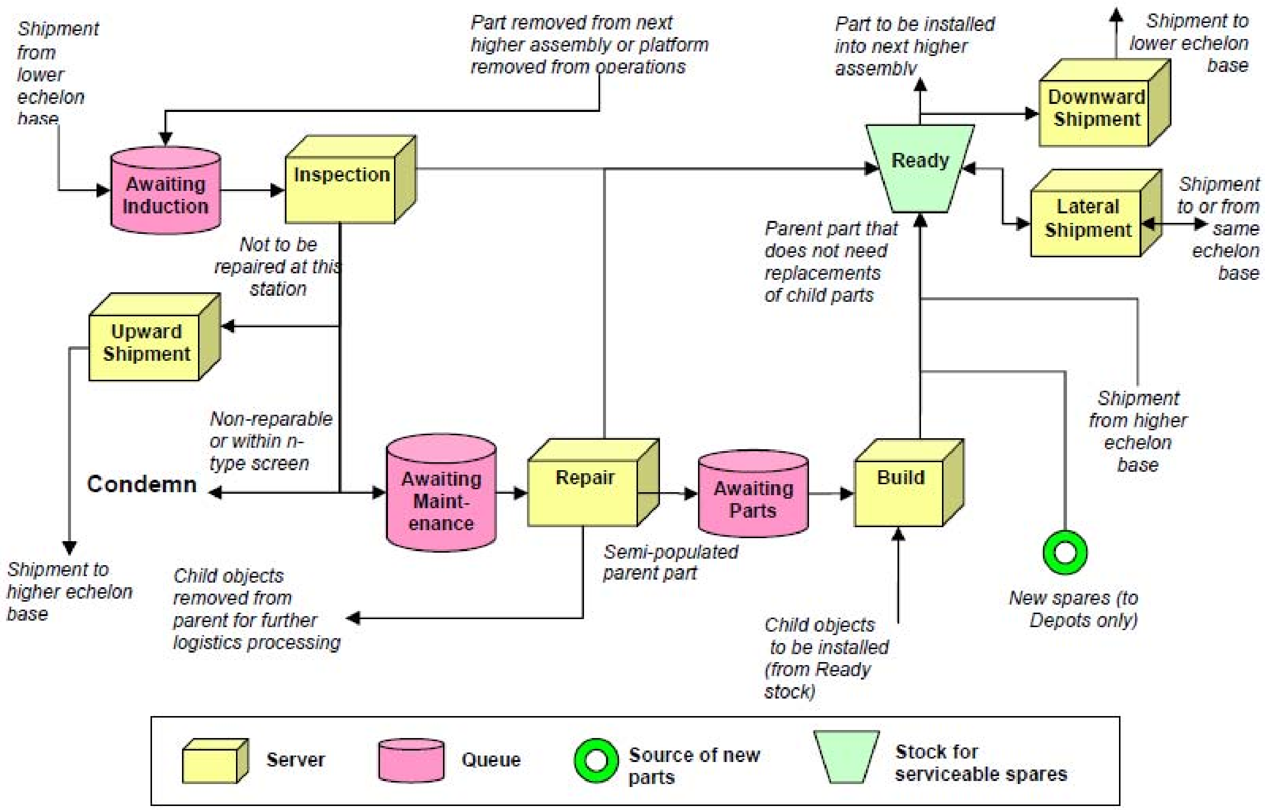


Figure #2 shows the logical flow of LRUs through the repair process. This flow is iterated at each level of repair (Operational, Intermediate, Depot). The complete flow diagrams for the entire logistic model can be found in the TLCM-AT / ATLAST Technical Reference Guide.

Figure #2 – Repair System Flow Diagram



Baseline Model Analysis

The baseline model was created using the data provided in the previous chapter. This model was run under two different scenarios. First, the model was run with no spares in the system to provide insight into the level of spares required to achieve a ~95% Operational Availability (Ao) for the fleet at each operating base. This level of spares was held constant throughout the remainder of the analysis. Once the spares had been properly determined, the baseline model was run again to establish the current state sustainment cost for the fleet over the 5 year simulation cycle. Each scenario, including the baseline analysis, was replicated 100 times to improve the level of confidence in the results.

DOE Design for CBM Implementation

Six factors were chosen for this study to determine their effect on cost. These factors are all expected to be impacted to some extent by the implementation of CBM+ capabilities. The goal of this case study was to develop a robust methodology for analyzing the ROI of CBM+ implementation. In order to achieve that goal it is critical to understand which factors have the greatest effect on reducing cost. This will focus efforts on technologies and solutions that specifically impact those parameters. Table #16 shows the 6 factors that were chosen along with the rationale for choosing them.

Table #16 - Factor Selection

Factor	Justification
Failure Rate	More failures are expected over a finite time period since parts will be replaced prior to complete failure rather than at or after failure. Additional failures will also occur due to false alarms.
No Fault Found Rate	NFF rate is expected to increase due to false alarms. This will require someone to inspect but not repair the LRU when a false alarm occurs.
Discard Rate	More parts should be repairable since advance warning of an impending failure should prevent catastrophic failures.
Evac Probability	Effective diagnostics should allow repair of minor and detectable failure modes to be done at the intermediate level. Only major damage or failure modes requiring substantial teardown should need to be sent to the depot.
Inspect Time	Inspection time should be reduced on average since diagnostic codes should perform much of the troubleshooting process that was previously done manually.
Shipping Time	Shipping time for a replacement part should be reduced due to advanced warning of a failure and proactive planning of the maintenance event.

A 2-Level 1/4 Factorial DOE provides the necessary insight into the main effect factors that drive cost. The use of a fractional factorial design is an effective way to perform a screening experiment while minimizing the number of different scenarios that need to be run. Table #17 shows the DOE design matrix obtained from Minitab. It should be noted that a randomized RunOrder is not necessary in the simulation environment since there is no time based data trending to potentially align with the standard order.

Table #17 - Minitab 2-Level 1/4 Factorial Design Matrix

StdOrder	RunOrder	CenterPt	Blocks	Failure Rate	NFF Rate	Discard Rate	Evac Prob	Inspect Time	Shipping Time
1	15	1	1	-1	-1	-1	-1	-1	-1
2	14	1	1	1	-1	-1	-1	1	-1
3	10	1	1	-1	1	-1	-1	1	1
4	13	1	1	1	1	-1	-1	-1	1
5	5	1	1	-1	-1	1	-1	1	1
6	2	1	1	1	-1	1	-1	-1	1
7	6	1	1	-1	1	1	-1	-1	-1
8	9	1	1	1	1	1	-1	1	-1
9	16	1	1	-1	-1	-1	1	-1	1
10	7	1	1	1	-1	-1	1	1	1
11	1	1	1	-1	1	-1	1	1	-1
12	8	1	1	1	1	-1	1	-1	-1
13	3	1	1	-1	-1	1	1	1	-1
14	11	1	1	1	-1	1	1	-1	-1
15	4	1	1	-1	1	1	1	-1	1
16	12	1	1	1	1	1	1	1	1

The matrix above represents the high and low factor values as coded variables. This normalizes the data so that factors with significantly different actual changes in their units can be uniformly compared against one another. Table #18 lists the actual changes that were made to these factors for the two set points and Table #19 shows the engineering values.

Table #18 - Factor Values (% change from Baseline)

Factor	**-1**	**1**
Failure Rate (#/1000 Miles)	Baseline	Baseline + 10%
No Fault Found Rate	Baseline	Baseline + 5%
Discard Rate	Baseline – 25%	Baseline
Evac Probability	Baseline – 25%	Baseline
Inspect Time	Baseline – 75%	Baseline
Shipping Time	Baseline – 25%	Baseline

Table #19 - Engineering Values / Actual Setpoints

Parameter Name	Platform: HEMTT	LRUs: Engine	Transmission	Battery	Alternator	Starter
-1						
Failure Rate (#/1000 miles)		0.00179	0.00203	0.00814	0.00358	0.00349
No Fault Found	0	0	0	0	0	0
Discard	0	0.17925	0.15	0.6	0.1125	0.15
Evac Prob	0	0.75	0.75	0	0.75	0.75
O Inspect Mean (Days)	0.05	0	0	0.025	0	0
I Inspect Mean (Days)	0	0.125	0.125	0	0.025	0.025
D Inspect Mean (Days)	0	0.125	0.125	0	0.025	0.025
		Time (Days)				
Shipping Time (O - I Level)		0.75				
Shipping Time (O - D Level)		12.75				
Shipping Time (I - D Level)		12.75				
Shipping Time (I - O Level)		0.75				
Shipping Time (D - I Level)		46.5				
Shipping Time (D - O Level)		46.5				
1						
Failure Rate (#/1000 miles)		0.00197	0.00224	0.00895	0.00394	0.00384
No Fault Found	0	0.05	0.05	0.05	0.05	0.05
Discard	0	0.239	0.2	0.8	0.15	0.2
Evac Prob	0	1	1	0	1	1
O Inspect Mean (Days)	0.2	0	0	0.1	0	0
I Inspect Mean (Days)	0	0.5	0.5	0	0.1	0.1
D Inspect Mean (Days)	0	0.5	0.5	0	0.1	0.1
		Time (Days)				
Shipping Time (O - I Level)		1				
Shipping Time (O - D Level)		17				
Shipping Time (I - D Level)		17				
Shipping Time (I - O Level)		1				
Shipping Time (D - I Level)		62				
Shipping Time (D - O Level)		62				

The downside to fractional factorial DOEs is that various interactions become confounded (aliased) with the main factor effects and other interactions. Table #20 shows the alias structure for this design matrix. The main effects are aliased with both 3-way and 5-way interactions. This is not a significant concern since higher order interactions are not anticipated to be significant for this model. One potential downside to the 1/4 factorial design is that 2-way interactions, which may be significant, will be aliased with each other and therefore unable to be tested for significance in this initial experiment. If this analysis were being run using real data, and with the intent of providing real results, the initial screening experiment would be followed by a Full Factorial design using any factors that were found to be significant main effects or that are part of an aliased 2-way interaction term that is found to be significant.

Table #20 – ¼ Factorial Alias Structure

I + ABCE + ADEF + BCDF
A + BCE + DEF + ABCDF
B + ACE + CDF + ABDEF
C + ABE + BDF + ACDEF
D + AEF + BCF + ABCDE
E + ABC + ADF + BCDEF
F + ADE + BCD + ABCEF
AB + CE + ACDF + BDEF
AC + BE + ABDF + CDEF
AD + EF + ABCF + BCDE
AE + BC + DF + ABCDEF
AF + DE + ABCD + BCEF
BD + CF + ABEF + ACDE
BF + CD + ABDE + ACEF
ABD + ACF + BEF + CDE
ABF + ACD + BDE + CEF

Chapter V – Analysis & Results

Five Year Fleet Sustainment Costs

Table #21 shows the cost data that was calculated for each scenario that was run. The actual output from the model is the number of events (inspect, repair, condemnation) that occur at each level of maintenance (operational, intermediate, depot). The cost calculation had to take into consideration the labor, parts, or replacement costs that would apply to that type of event. All calculations made are contained in an Excel Spreadsheet HEMTT Case Study DOE Results.xlsx submitted electronically as an appendix to this report. These costs could be evaluated in many different ways to provide additional insight into the impact of the design factors that were chosen for the experiment. For instance, each type of cost (inspection, repair, and spares) could be evaluated to see where the greatest impact is made from the proposed design change. Total cost could be evaluated in terms of operating hours achieved by the fleet as a way to evaluate the impact that the proposed design change might have on fleet availability. For this case study the evaluation will be based on the total fleet sustainment cost over the five year simulation period.

Table #21 – DOE Cost Summary

	Five Year Sustainment Costs				
Database Name	Inspect	Repair	Spares	Total	Cost per Oper Hour Achieved
TARDEC HEMMT No Sensor DOE Baseline	$37,622	$460,772	$377,651	$876,046	$1.81
TARDEC HEMMT No Sensor DOE1	$8,365	$440,890	$301,325	$750,580	$1.55
TARDEC HEMMT No Sensor DOE2	$36,153	$486,143	$291,614	$813,910	$1.68
TARDEC HEMMT No Sensor DOE3	$33,181	$415,393	$284,375	$732,949	$1.51
TARDEC HEMMT No Sensor DOE4	$9,108	$451,589	$319,344	$780,042	$1.61
TARDEC HEMMT No Sensor DOE5	$33,014	$405,513	$378,728	$817,255	$1.69
TARDEC HEMMT No Sensor DOE6	$9,147	$452,816	$404,871	$866,834	$1.79
TARDEC HEMMT No Sensor DOE7	$8,260	$389,621	$351,833	$749,715	$1.55
TARDEC HEMMT No Sensor DOE8	$36,375	$419,469	$396,161	$852,005	$1.76
TARDEC HEMMT No Sensor DOE9	$9,452	$504,802	$271,772	$786,027	$1.62
TARDEC HEMMT No Sensor DOE10	$41,891	$558,438	$299,776	$900,106	$1.86
TARDEC HEMMT No Sensor DOE11	$38,500	$483,527	$287,767	$809,794	$1.67
TARDEC HEMMT No Sensor DOE12	$10,488	$529,219	$297,519	$837,226	$1.73
TARDEC HEMMT No Sensor DOE13	$37,519	$463,832	$339,491	$840,843	$1.73
TARDEC HEMMT No Sensor DOE14	$10,394	$510,541	$412,921	$933,856	$1.93
TARDEC HEMMT No Sensor DOE15	$9,537	$449,896	$352,307	$811,741	$1.67
TARDEC HEMMT No Sensor DOE16	$41,880	$480,609	$417,950	$940,439	$1.94

DOE Results

The total costs were put into Minitab and the analysis performed in two different ways. First the analysis was run including 2-way interactions in addition to the main effects. Figure #3 shows the results obtained from Minitab. The Minitab projects are contained on disk in the appendix.

Figure #3 – Minitab Output for Analysis Including 2-way Interactions

Factorial Fit: Total Cost versus Failure Rate, NFF Rate, ...

Estimated Effects and Coefficients for Total Cost (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		826458	4227	195.53	0.000
Failure Rate	78189	39095	4227	9.25	0.011
NFF Rate	-24438	-12219	4227	-2.89	0.102
Discard Rate	50257	25128	4227	5.95	0.027
Evac Prob	62093	31046	4227	7.35	0.018
Inspect Time	23910	11955	4227	2.83	0.106
Shipping Time	5933	2967	4227	0.70	0.555
Failure Rate*NFF Rate	-1811	-905	4227	-0.21	0.850
Failure Rate*Discard Rate	15206	7603	4227	1.80	0.214
Failure Rate*Evac Prob	12616	6308	4227	1.49	0.274
Failure Rate*Inspect Time	-1784	-892	4227	-0.21	0.852
Failure Rate*Shipping Time	6673	3336	4227	0.79	0.513
NFF Rate*Evac Prob	9030	4515	4227	1.07	0.397
NFF Rate*Shipping Time	-1825	-913	4227	-0.22	0.849

S = 16906.8   R-Sq = 99.01%   R-Sq(adj) = 92.54%

Analysis of Variance for Total Cost (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	6	54795557336	54795557336	9132592889	31.95	0.031
2-Way Interactions	7	2104964381	2104964381	300709197	1.05	0.569
Residual Error	2	571682913	571682913	285841457		
Total	15	57472204630				

From this analysis it can be seen that none of the 2-way interactions were found to be significant. This is a powerful discovery. Since no 2-way interaction is significant, the aliasing of 2-way interaction is mute. As a result of this finding, and the unlikelihood of significant 3-way interaction, the DOE was reanalyzed using main effects only. Figure #4 shows these results. Further experimentation to resolve aliasing would appear to be unnecessary at this point.

Figure #4 – Minitab Output for Analysis for Main Effects Only

Factorial Fit: Total Cost versus Failure Rate, NFF Rate, ...

Estimated Effects and Coefficients for Total Cost (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		826458	4311	191.69	0.000
Failure Rate	78189	39095	4311	9.07	0.000
NFF Rate	-24438	-12219	4311	-2.83	0.020
Discard Rate	50257	25128	4311	5.83	0.000
Evac Prob	62093	31046	4311	7.20	0.000
Inspect Time	23910	11955	4311	2.77	0.022
Shipping Time	5933	2967	4311	0.69	0.509

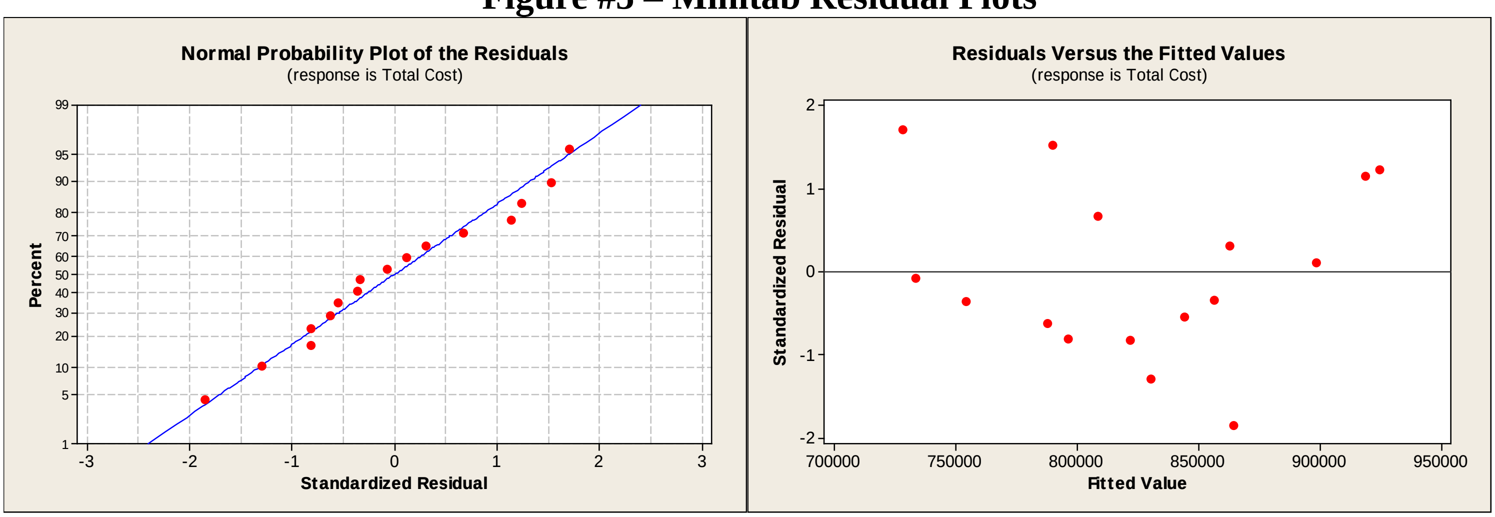
S = 17245.4   R-Sq = 95.34%   R-Sq(adj) = 92.24%

Analysis of Variance for Total Cost (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	6	54795557336	54795557336	9132592889	30.71	0.000
Residual Error	9	2676647294	2676647294	297405255		
Total	15	57472204630				

The results above show that all of the main effects are significant except for Shipping Time. It also shows that R-Sq(adj) = 92.24% which means that the model that has been fit using only the significant main effects accounts for 92% of the variability in total cost. Models with R-sq(adj) values greater than 70 – 75% are usually considered acceptable for screening experiments such as this. Figure #5 shows the Normal and Residuals vs Fitted Values plots for the standardized residuals. These help to add confidence that the model results are sound. The standardized residuals are expected to be normally distributed and randomly spread across the fitted values. Neither of these plots indicated anything that would raise significant concern about the conclusions drawn from the analysis.

Figure #5 – Minitab Residual Plots



DOE Design Space Discussion

In this experiment Shipping Time was not found to be a significant factor in determining sustainment cost even though logistic down time is usually a factor that needs to be considered in this type of system. This raises a question about other potential factors that were not considered in the experiment. It also highlights an important fact that needs to be considered when interpreting the analysis results from a DOE. The analysis of any DOE only applies to the design space that is included in the experiment. This design space defines a multidimensional inference space where the model's predictions can be expected to provide valid results. Attempting to use this model to make predictions outside of the design space is a common and potentially costly mistake.

As an example, consider the impact of shipping time on fleet operational availability (Ao). If a platform is down while waiting for parts then it is unavailable to perform its mission and this would require other platforms to absorb this additional operating time in order to maintain the total fleet Ao. This implies a dependency on the number of platforms at a given location and the expected OPTEMPO for that local fleet. Additionally, the time required to ship a new or repaired part only becomes an operational factor if a spare is not readily available, and the level of spares only becomes a factor if the number of failures at a location cannot be supported by the spares available to that location. This simple example shows how shipping time could intuitively be a cost driving factor in some cases and that it is the limitation of the experiment's design space that has it be insignificant in this case.

ROI For CBM+ Implementation

Figure #6 is the Minitab output that indicates the model coefficients for the uncoded space. In this experiment, the factors were defined as a percentage change from the baseline.

Figure #6 – Minitab Regression Model Coefficients

```
Estimated Coefficients for Total Cost using data in uncoded units

Term              Coef
Constant       -416224
Failure Rate    781892
NFF Rate       -488750
Discard Rate    201027
Evac Prob       248371
Inspect Time   31880.0
Shipping Time  23732.0
```

These coefficients can be written as a linear model in terms of a percentage change from baseline as indicated in Table #22 below. The variables can take on values within the design space constraints as discussed in the previous section.

Table #22 - Cost Regression Model

Factor	Coeff	Variable	Constraint
Constant	-$416,224	N/A	N/A
Failure Rate	$781,892	1 + %increase	< 10% increase
NFF Rate	-$488,750	0 + %increase	< 5% increase
Discard Rate	$201,027	1 - %decrease	<25% decrease
Evac Prob	$248,371	1 - %decrease	<25% decrease
Inspect Time	$31,880	1 - %decrease	<75% decrease

Using this cost model we can evaluate the baseline sustainment costs, the expected costs for CBM+ enabled vehicles, and the ROI payback period. These results are shown in Table #23.

Table #23 - CBM+ Implementation ROI

	Factor	Coeff	Variable	Costs
Baseline Cost Model Results	Constant	-$416,224	N/A	-$416,224
	Failure Rate	$781,892	1	$781,892
	NFF Rate	-$488,750	0	$0
	Discard Rate	$201,027	1	$201,027
	Evac Prob	$248,371	1	$248,371
	Inspect Time	$31,880	1	$31,880
	5yr Sustainment Costs			$846,946
CBM Solution Cost Model Results	Factor	Coeff	Variable	Costs
	Constant	-$416,224	N/A	-$416,224
	Failure Rate	$781,892	1.1	$860,081
	NFF Rate	-$488,750	0.05	-$24,438
	Discard Rate	$201,027	0.75	$150,770
	Evac Prob	$248,371	0.75	$186,278
	Inspect Time	$31,880	0.25	$7,970
	5yr Sustainment Costs			$764,438
Implementation Costs	Cost / Platform			$15,000
	# of Platforms			230
	Total			$3,450,000
ROI Analysis	5Yr Sustainment Savings			$82,508
	Payback Period @ $15K/platform (years)			209
	Cost / Platform for 10 year payback			$717

Chapter VI – Conclusions

CBM+ ROI

This case study attempted to perform a more realistic analysis of the potential return on investment that could be realized from implementing CBM+ capabilities on U.S. Army tactical vehicles. The approach that was chosen was one that embraced the uncertainty and time dependent nature of the problem, which had been ignored in all prior ROI analyses. The challenges in obtaining real data prevented this case study from providing actionable information to the Army, but it was nonetheless successful in demonstrating a valid approach to the problem that can be utilized once real data is available.

The results of this experiment indicate that it would not be cost effective to implement CBM+ capabilities on the proposed platforms. The ~210 year payback period ignores the time value of money and therefore is the most optimistic of estimates. The analysis showed that only main effects, and possibly the aliased 3-way interactions, were significant in determining sustainment costs. None of the 2-way interactions were significant. The analysis also showed that Shipping Time was not a significant factor even with a 75% reduction from the baseline. This was contrary to what was initially thought to be true and further supports the use of DOEs to gain insight into complex systems and what really are the cost driving inputs.

One final interesting finding is that the cost savings obtained from the CBM implementation in this case study was roughly 10% of the baseline sustainment cost value. Comparing the results of the simulation to the previously performed TWV CBM ROI Analysis it can be shown that both approaches reveal a 14yr payback period for a $1000 / platform implementation cost. This is obviously an incredible coincidence given the two drastically different approaches, the different number of vehicles involved, and different per platform sustainment costs, but it is interesting nonetheless.

Use of Dynamic Stochastic Discrete Event Simulation

This case study successfully demonstrated a methodology for utilizing modeling and simulation to evaluate CBM+ implementation costs and potential return on investment opportunities. The use of a dynamic stochastic simulation enables the various model input parameters to capture uncertainty in parameter estimates which is beneficial for evaluating costs in the face of real world induced variability. The use of discrete event simulation is an effective way to minimize simulation processing time for evaluating systems where the system behavior between individual discrete events are insignificant to the response variables being measured. Queuing systems (i.e. supply, maintenance, shipping, etc) are ideal candidates for this type of simulation approach.

A variety of discrete event simulation software tools are available to perform this kind of modeling and analysis. The Clockwork Solution Inc Total Life Cycle Management Assessment Tool (TLCM-AT) proved to be a very efficient tool in that the major logistic systems, the data that defines these systems, and the interactions between them have already been defined. Additionally, since this tool was developed for the military the structure of the systems are well defined in terms of how the military functions in an operational environment. This particular case study had a very narrow focus and barely scratched the surface of this tool's capabilities. With that said, this case study also demonstrated the need for an experienced analyst to make use of this tool. A user who does not understand how to setup valid experiments, and analyze the results from them, could make very bad decisions with the results obtained from this tool.

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Appendix
(Electronic Submission)

File Name	Description
HEMTT CASE STUDY DOE1.mpj	**Minitab Project Analysis for main effects and 2-way interactions**
HEMTT CASE STUDY DOE2.mpj	**Minitab Project Analysis for main effects only**
HEMTT Case Study DOE Results.xlsx	**Excel Spreadsheet with all cost calculations**